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Review Article

Exo-Ocean Exploration with Deep-Sea Sensor and Platform Technologies

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Abstract

One of Saturn's largest moons, Enceladus, possesses a vast extraterrestrial ocean (*i.e.,* exo-ocean) that is increasingly becoming the hotspot of future research initiatives dedicated to the exploration of putative life. Here, a new bio-exploration concept design for Enceladus' exo-ocean is proposed, focusing on the potential presence of organisms across a wide range of sizes (*i.e.,* from uni- to multicellular and animal-like), according to state-of-the-art sensor and robotic platform technologies used in terrestrial deep-sea research. In particular, we focus on combined direct and indirect life-detection capabilities, based on optoacoustic imaging and passive acoustics, as well as molecular approaches. Such biologically oriented sampling can be accompanied by concomitant geochemical and oceanographic measurements to provide data relevant to exo-ocean exploration and understanding. Finally, we describe how this multidisciplinary monitoring approach is currently enabled in terrestrial oceans through cabled (fixed) observatories and their related mobile multiparametric platforms (*i.e.,* Autonomous Underwater and Remotely Operated Vehicles, as well as crawlers, rovers, and biomimetic robots) and how their modified design can be used for exo-ocean exploration. Key Words: Exo-ocean—Enceladus—Deep-sea technology—Autonomous underwater vehicles—Crawlers—Cryobots. Astrobiology 20, xxx–xxx.

1. Introduction

Liquid water is present in the form of vast extraterrestrial oceans (*i.e.,* exo-oceans) on various icy moons of our solar system (NASEM, 2018; Hendrix *et al.,* 2019; Kamata *et al.,* 2019). Five icy moons have been confirmed as ocean worlds, namely, three satellites of Jupiter (Europa, Ganymede, and Callisto) and two of Saturn (Enceladus and Titan, the latter with an exo-ocean below a thick hydrocarbon layer; Iess *et al.,* 2012). Another four are likely to host a subsurface ocean, such as Saturn's moon Dione, Neptune's icy moon Triton, and the dwarf planet Pluto. Moreover, the dwarf planet Ceres seems to have at least a subsurface sea (Henin, 2018).

The primary conditions under which we could expect to find extant life in exo-oceans (although this hypothesis is still uncertain at this stage of scientific research) are the presence of energy sources that facilitate a non-equilibrium thermodynamic state of a marine-like medium containing abundant organic compounds (Schwieterman *et al.,* 2018).

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Among the above-mentioned icy moons, Enceladus and Europa meet these conditions. Both host large water-based oceans in which geothermal activity is present and where life could be possible (Manga and Wang, 2007; Iess *et al.,* 2014; Deamer and Damer, 2017; Rovira-Navarro *et al.,* 2019). In fact, relevant geothermal activity has been imaged on both moons by the Cassini-Huygens probe as well as by the Galileo and Hubble Space Telescope space missions (Henin, 2018). Notwithstanding, the presence of organic molecules as markers for more complex compounds (*e.g.,* amino acids and nucleotides), dissolved into a salty marine medium, has been directly indicated by the Cassini-Huygens probe of Enceladus' plumes (McKay *et al.,* 2014; Hsu *et al.,* 2015; Kimura and Kitadai, 2015; Mann, 2017; Postberg *et al.,* 2018). This fact makes Enceladus the most promising site for extraterrestrial life exploration (Postberg *et al.,* 2018).

Enceladus is 500 km in diameter with a gravity field of only 1.2% that of Earth (Manga and Wang, 2007). Its vast exo-ocean mechanically decouples the rocky core from the exterior ice shell (Thomas *et al.,* 2016). The water body is kept fluid by geothermal activity in combination with tidal warming through Saturn's tidal pull forces and by ice shell thickness variations, all likely contributing to abrupt changes in water column pressure (Hussmann *et al.,* 2006; Manga and Wang, 2007; Jansen, 2016; Saxena *et al.,* 2018; Hemingway and Mittal, 2019; Neveu and Rhoden, 2019). Pressure changes result in active geysers, which eject water plumes into space, creating the phenomenon of cryovolcanism (FIG. 1). Strong geothermal gradients and high pressure produce large fluxes of hot water, transported through the ice shell via cracks and crevasses (Choblet *et al.,* 2017). Due to decompression shocks, water suddenly evaporates and freezes once it emerges into space, dropping back on the surface as snow (Běhounková *et al.,* 2017).

Exo-ocean salinity conditions on Enceladus seem to be similar to those on Earth (Fifer *et al.,* 2019), which would lead to a water density of approximately 1020 kg/m^3, similar to that of terrestrial oceans (Hemingway and Mittal, 2019). However, the average depth is much higher, being approximately between 30 and 50 km (Iess *et al.,* 2014, Hemingway and Mittal, 2019). This would generate a total volume of around 40% of the mass of the moon itself (Čadek *et al.,* 2016). Enceladus' ice shell has an average thickness of 20–30 km with reduced thickness at the South Pole (Čadek *et al.,* 2016; Lucchetti *et al.,* 2017; Hemingway and Mittal, 2019).

Enceladus' exo-ocean seems to have been in a fluid state for a time span equivalent to that of the oceans on Earth (Choblet *et al.,* 2017; Lunine, 2017; Jia *et al.,* 2018), potentially allowing abiogenesis and evolution of unicellular and multicellular-like life-forms (Barge *et al.,* 2017, 2019). Geothermal activity seems to be a component that favored the emergence of primordial life on Earth, driving its evolution in the deep sea (Baross and Hoffman, 1985; Burcar *et al.,* 2015). Similarly, exo-ocean geothermal activity could favor the evolution of organisms with chemosynthetic metabolic pathways analogous to those documented in highly productive hydrothermal communities on Earth (*e.g.,* Chyba and Hand, 2001; Barge and White, 2017; Seewald, 2017). During the geological history, those exo-ocean hydrothermal vent systems could have evolved into biodiversity-rich environments with chemosynthetic autonomous communities of primary producers, grazers, predators, scavengers, and remineralizing organisms (*e.g.,* Lelièvre *et al.,* 2018).

Unfortunately, exploration for life in Enceladus' exo-ocean presents technological challenges of much higher complexity than the exploration of any location in the deep sea on Earth. Instrument payloads will likely have a constraining effect on their use for the exploration of Enceladus over the next decades, although the weight of their casing can be greatly reduced compared to ocean instrumentation on Earth due to the reduced gravity on Enceladus. Moreover, the penetration of a potentially large ice shell requires tools to carve or melt tunnels on the scale of kilometers, in order to open the passage for any marine-like exploring platforms (Weiss *et al.,* 2008; Flögel *et al.,* 2018). Anyway, those technological efforts are already in place. Different projects such as the Enceladus Explorer (EnEx) and the Europa Explorer (EurEx) (Konstantinidis *et al.,* 2015), as well as the Very-Deep Autonomous Laser-Powered Kilowatt-Class Yo-Yoing Robotic Ice Explorer (VALKYRIE) are presently focusing on autonomous navigation and control of robotic systems on, and especially under, exo-ocean ice shells.

1.1. Objectives

Motivated by data indicating that Enceladus' exo-ocean may host complex organic life and given the time span of its existence as a fluid body (Postberg *et al.,* 2018), we provide a perspective for implementing its environmental and life-oriented exploration based on available deep-sea technologies. We first describe high-priority sensors that are currently in use for marine sciences, when aiming at the characterization of pelagic and benthic seascapes, whose environmental conditions may affect life itself. Then we focus on those sensors that allow the detection of multicellular life-forms (*i.e.,* animal-like), which is, to date, primarily carried out by imaging systems. At the same time, we also describe complementary molecular methods for indirect traceability of life (that would also allow the capability of detection of unicellular life). Later, we illustrate the different marine monitoring platforms and their assemblage into high-tech networks that could be used as test beds for exo-ocean life-detecting technologies. Ultimately, we propose a forward-looking pathway for environmental exploration of exo-oceans based on adapted versions of previously described sensor and platform technologies.

2. Deep-Sea Sensors for Exo-Ocean Reckoning and Life Detection

Prokaryotic-like life (*i.e.,* unicellular) could be (theoretically) inhabiting exo-oceans (Merino *et al.,* 2019). Traces of biological activity could then be detectable from tens of meters up to kilometers as has been accomplished on Earth's oceans with available deep-sea sensor technologies (Aguzzi *et al.,* 2019).

At the same time, other sensors could be used to characterize exo-ocean seascapes, including circulation and bathymetry, as relevant ancillary information for describing ongoing oceanographic and geochemical processes, which may create conditions conducive to life itself. To date, a diversified group of environmental sensors are being used in a remote, synchronous, and long-lasting fashion at virtually

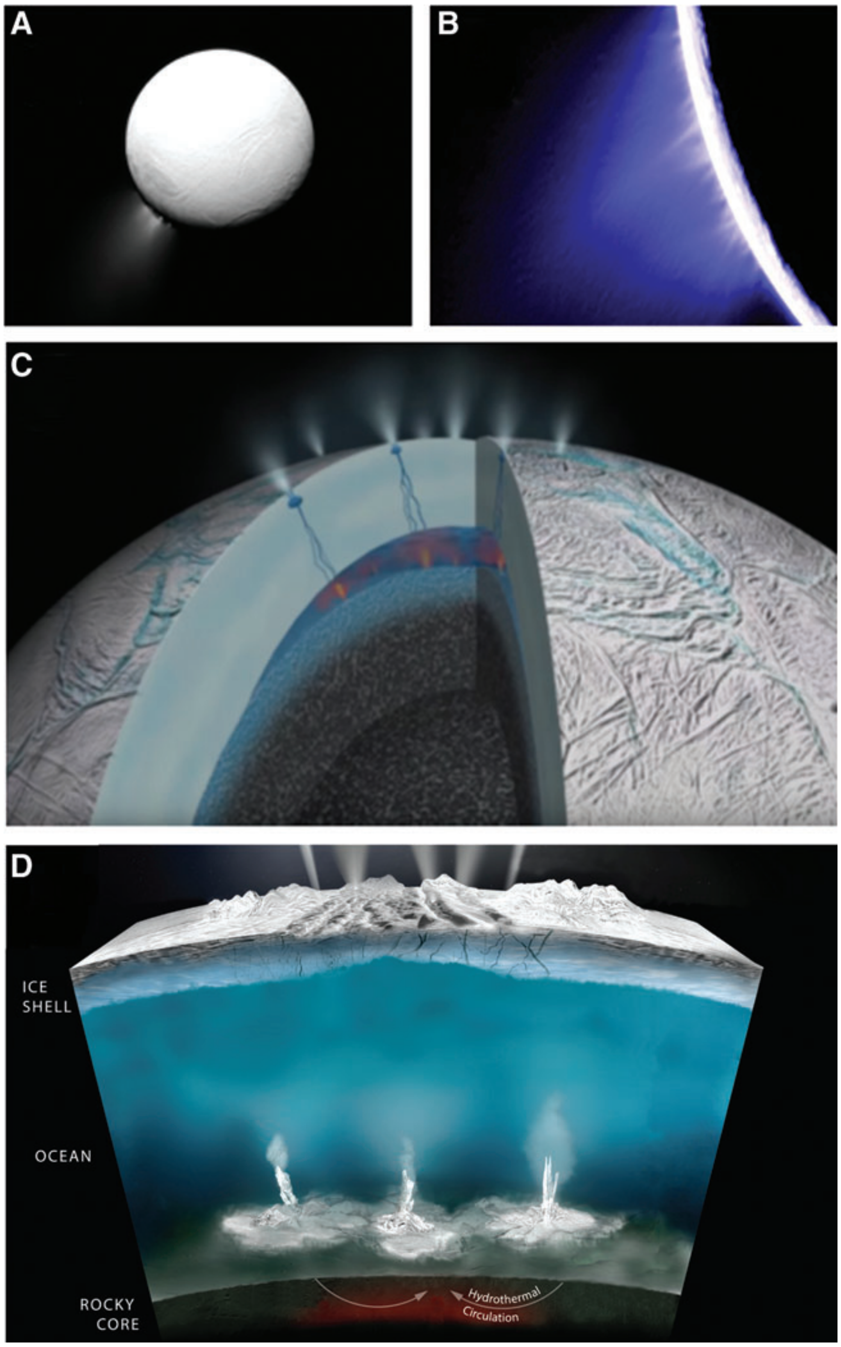

FIG. 1. Enceladus is a small moon (diameter of about 500 km) that became a research hotspot when the space probe Cassini-Huygens discovered evidence of cryovolcanism, including exhalations into space by geysers in 2005. (**A** and **B**) Imaging of individual jets spurting ice mixed with vapor and trace organic compounds. (**C** and **D**) proposed mechanism generating observed geysers. Sources: DCode by Discovery; https://www.youtube.com/watch?v=MjOpZrYLE1U; NASA/JPL/Space Science Institute; https://www.jpl.nasa.gov/news/news.php?feature=3382. Color images are available online.

any depth of benthic and pelagic oceanic realms (Danovaro *et al.,* 2020). Below, we describe the most relevant sensors for acquiring oceanographic and geochemical information; then we move to those sensors, providing information on potential life activity (TABLE 1).

It should be noticed that current marine sensors are far from being exo-ocean flight-ready in terms of mass, robustness, autonomy, reliability, and so on. Such a development would be an engineering effort, requiring important economic sustainment, the description of which is out of the scope of this work. Moreover, the environmental knowledge needed to use these sensors *in situ* in an exo-ocean is not yet currently available. Therefore, due to this limitation, we describe them assuming that Enceladus' water medium conditions are similar to those present in Earth's oceans (Fifer *et al.,* 2019; Hemingway and Mittal, 2019). In any case, such sensors are already conceived to currently operate in harsh deep-sea conditions (Ramirez-Llodra *et al.,* 2010), including darkness, high pressure, extreme low or very high temperatures (*e.g.,* 1–8°C at seabed and around 400°C close to hydrothermal vent emissions), and variable turbidity (Aguzzi *et al.,* 2019).

2.1. Oceanographic and geochemical sensors

Enceladus' exo-ocean seascapes can be explored with different environmental sensors (TABLE 1). The concentration of floating particles as well as their size and organic

Table 1. Deep-Sea Multiparametric Sensors That Could Operate Synchronously for the General Exploration and Detection of Putative Life in Enceladus' Exo-Oceans

Measured variable	*Sensors*	*Operational realm*	*Exo-oceans exploration goal*	*In use*	*Priority*
Geological	Turbidimeters	Pelagic and Benthic/Under ice shell	Turbidity from resuspension phenomena and benthopelagic (crust-water mass) coupling flux matter	*	
	Side-Scan Sonar, Multi-beam, Laser scanning (*e.g.,* LiDAR)	Benthic/Under ice shell	Benthic topography and geomorphological characterization, gas bubbling characterization		*
	Gamma counter	Pelagic and Benthic	Radiogenic heating and energy sources for life (radiolysis of water)	*	
	Laser diffraction	Pelagic	Particle size and concentration	*	
	Fiber optic cables	Under ice	High-resolution strain dynamism	*	
	Seismometer	Benthic/Under ice shell	Seismic activity	*	
Chemical	Carbon anhydride	Pelagic and Benthic/Under ice shell	Ocean chemical composition/Monitoring for biosignatures	*	
	Nitrates	Pelagic and Benthic/Under ice shell	Ocean chemical composition/Monitoring for biosignatures	*	
	Oxygen	Pelagic and Benthic/Under ice shell	Ocean chemical composition/Monitoring for biosignatures	*	
	Phosphates	Pelagic and Benthic/Under ice shell	Ocean chemical composition/Monitoring for biosignatures	*	
	Sulfates	Pelagic and Benthic/Under ice shell	Ocean chemical composition/Monitoring for biosignatures	*	
	Methane	Pelagic and Benthic/Under ice shell	Ocean chemical composition/Monitoring for biosignatures	*	
	pH	Pelagic and Benthic/Under ice shell	Acidity ranges and carbon geochemical cycle	*	
	Redox potential	Benthic	Oxygen content into sediments		*
	Mass spectroscopy–based methods (Raman, laser-induced)	Pelagic and Benthic/Under ice shell	Biomolecules as biosignature (*e.g.,* amino acids, hydrocarbon compounds), non-nucleic acid heteropolymers as genetic information carriers, and essential transition metals (sustaining enzyme functioning)		*
Oceanographic	Temperature (CTD)	Pelagic and Benthic	Hydrothermal fluxes (*e.g.,* convection)	*	
	Salinity (CTD)	Pelagic and Benthic	Brine exclusion (freezing), water-rock interaction (thermal inputs)	*	
	Current speed (ADCP, Doppler)	Pelagic and Benthic/Under ice shell	Current flows for tidal bulge or hydrothermal convection	*	
	Acoustic Current Meter	Pelagic and Benthic/Under ice shell	Measuring turbulence/mixing at ice-water interface	*	
	Water Column Pressure	Benthic	Depth-dependent water column weight and tidal bulge	*	
Biologic	Optoacoustic (HD, 3D, Stereo, Hyperspectral) and acoustic imaging (Multi-beam Cameras and Rotary Sonar)	Pelagic and Benthic/Under ice shell	Sessile, motile fauna and bacterial mat presence identification and quantification	*	
	Geo-sonars (Acoustic imaging)	Benthic/Under ice shell	Infauna presence and quantification within substrates (*e.g.,* ice)		*
	Micro-Imaging and Aquatic Microscopy (*e.g.,* CPI)	Pelagic	Microorganism presence and characterization	*	
	Photomultipliers and Low-Light Imaging	Pelagic	Bioluminescence as proxy for bacterial presence and organisms' light-based communication activity	*	
	Hydrophones (PAM)	Pelagic	Broad acoustic panoramas (*i.e.,* geophony) and organisms' sound-based activity (*i.e.,* biophony as echolocation or vocalization)	*	
	Electric charge readers	Pelagic	Organisms electrical-based activity (*e.g.,* electrolocation, electrocommunication)		*
	Nucleic acid detectors	Pelagic and Benthic/Under ice shell	DNA/RNA traceability		*

These are described according to their present use in marine sciences (In use) and potential applicability, since relevant but not yet fully developed (Priority).
ADCP = Acoustic Doppler Current Profilers; CPI = Continuous Particle Imaging; CTD = Conductivity-Temperature-Density; PAM = Passive Acoustic Monitoring.

or inorganic composition can be measured by light absorbance sensors, including laser diffraction and Raman spectroscopy together with a wide range of related properties (Boss *et al.,* 2015). Floating particle size may be controlled by turbulence and by biogenic activity (*e.g.,* marine snow-like aggregates; Turner, 2015), being the product of resuspension from deeper seafloors.

As salinity and carbon-dioxide contents of the exo-oceans seem to be similar to those on Earth (Fifer *et al.,* 2019; Hemingway and Mittal, 2019), Conductivity-Temperature-Density (CTD) probes as well as oxygen and pH sensors could also be used as relevant markers for proteins and nucleic acids stability and to set the boundaries for metabolism existence as we know it on Earth (NASEM, 2018). Nitrate, phosphate, and even methane sensors could be used as well, since they efficiently operate in environments where marked fluctuations in those dissolved gases occur at different spatiotemporal scales (*e.g.,* Thomsen *et al.,* 2012; Doya *et al.,* 2015). In the case of Enceladus, measurements of dissolved methane may be of relevance in order to highlight the presence of biological chemosynthetic activity as it occurs on Mars (Formisano *et al.,* 2004). The occurrence of essential nutrients such as nitrates and phosphates may also provide relevant hints on the distribution and productivity of life into the exo-ocean itself, and when these data are coupled with those from currents (see next section), circulation effects on potential biological productivity can be modeled (Olson *et al.,* 2019).

2.2. Sonars

Enceladus' exo-ocean current regimes are presently unknown, and complex hydrodynamic seascapes may occur below the ice shell, within the water column, and near the rocky core (*e.g.,* Rovira-Navarro *et al.,* 2019). Scientific findings on Earth have shown that currents may deeply alter life existence, determining the concentration of life-limiting gases (*e.g.,* oxygen minimum zones in oceans; Paulmier and Ruiz-Pino, 2009) and nutrient dispersal (Olson *et al.,* 2019), thus conditioning the appearance of organisms as sessile or motile forms.

Active acoustic tools (*e.g.,* Acoustic Doppler Current Profilers, ADCP), commonly used in oceanographic studies for acquiring flow speed and direction data, could be deployed faced down, below the ice shell (TABLE 1) (Fifer *et al.,* 2019; Hemingway and Mittal, 2019). For example, Aquadopp models (Nortek[1]) working at 2000 kHz allow a maximum depth resolution of 6 km with an accuracy of 0.5 cm/s.

Multibeam Echo Sounders (MBES), based on the emission of multiple ultrasonic frequencies, are commonly used for the characterization of the seabed (Lo Iacono *et al.,* 2008; Lurton, 2010; Lecours *et al.* 2016), the analysis of the water column–seabed interface, and the identification of gas plumes (Colbo *et al.,* 2014; Innangi *et al.,* 2016; Zhao *et al.* 2017). When the MBES are combined with navigation data of a moving platform (see next section), a complete characterization of Enceladus' rocky nucleus surface could be obtained (*e.g.,* Wynn *et al.,* 2014). In a similar way to Earth's findings, the effects of bioturbation as well as the presence of biogenic structures (actual or fossil) could be revealed by recurrent marks on the seabed surface or specific geomorphologies (Baucon *et al.,* 2017). MBES systems could also be configured face-upward to scan the bottom of the ice shell, providing important information on its morphology and dynamics at the interface with the water (McPhail *et al.,* 2009; Dutrieux *et al.,* 2014a, 2014b).

Multibeam echo sounders can also be used for the quantification of animal presence in large volumes of water via the analysis of acoustic backscatter returns, when an adequate assessment of signal-to-noise ratio can be made (*e.g.,* Briseño-Avena *et al.,* 2015). Although preexisting knowledge on echo signature for acoustic signal cross-referencing is not yet available for exo-oceans and MBES cannot be used for the identification of any fauna, those sensors could be used to identify objects moving in the water column, thus contributing to the environmental characterization (Dunlop *et al.,* 2018).

Finally, acoustic tomography based on sound propagation could also be employed to measure temperature, currents, and internal tides among distant and time-keeping synchronized acoustic sources (Munk *et al.,* 1995; Finn and Rogers, 2017). Such technology could be used to derive large-scale information on exo-ocean circulation and geothermal activity. For example, acoustic tomography enabled the identification of localized convection ''chimneys'' in Greenland's deep sea (at 1800 m) that are caused by extreme surface winter cooling (Wadhams *et al.,* 2002). Similar techniques could be applied to detect exo-ocean geothermal fluxes.

2.3. Optical sensors

High-definition (HD) imaging is widely used in ecological exploration of Earth's deep-sea, and current tools may be used to identify the presence of fauna with sessile or motile morphological designs on icy moons, although that possibility is to date still highly uncertain (Newman, 2018). Within this context, fast-developing deep-sea imaging technologies centered on HD photogrammetry, stereo, hyperspectral, miniaturized cameras and low-light vision are established tools that permit assessment of the presence and activity of organisms (*e.g.,* Kokubun *et al.,* 2013; Bicknell *et al.,* 2016; Corgnati *et al.,* 2016, Marini *et al.,* 2018a). These imaging assets could be adapted for the identification of exo-oceanic fauna in a broad range of sizes (*i.e.,* equivalent to our prokaryotes, including bacterial mat formations, as well as micro-eukaryotes, micro- and meso-zooplankton, up to larger multicellular organisms). Those cameras require different levels of light intensity, which is a monitoring footprint with biological effects still under evaluation in deep-sea contexts (Aguzzi *et al.,* 2019).

2.4. Low-light imaging technologies

Different image-based technologies for life detection could also be used to avoid the exogenous light footprint. Such an imaging is capable of recording very low intensity emissions from organisms, as in the case of bioluminescence (see TABLE 1).

Environmental prerequisites that potentially favor bioluminescence existence in exo-oceans are light-deprivation

[1]https://www.nortekgroup.com/products/aquadopp-6000-m

and ecosystem stability as it occurs in Earth's deep sea. However, one should also consider the possibility that bioluminescence could be a non-existing phenomenon on Enceladus, even in the extreme case of having identified any life-form.

Bioluminescence is a ubiquitous phenomenon in environments that have been stable over large geological times on Earth (*i.e.,* marine as compared to freshwater, where only a few bioluminescent species are known) (Haddock *et al.,* 2010). Bioluminescence evolved independently, being present in most of the major marine phyla (Herring, 1987; Widder, 2010; Martini and Haddock, 2017; Martini *et al.,* 2019), as well as in some bacteria (Martini *et al.,* 2016). Bioluminescence is produced by organisms for predation, defense, and intraspecific communication (Haddock *et al.,* 2010), and organisms can emit it after mechanical stimulation at collisions (Craig *et al.,* 2011).

Calibrated high-resolution measurements of mechanically stimulated bioluminescence are made by the Underwater Bioluminescence Assessment Tool (UBAT), similar to a Multipurpose Bioluminescence Bathyphotometer (MBBP; Herren *et al.,* 2005). Other systems use a stimulating grid mounted on oceanographic instruments, such as CTD, to obtain vertical pelagic profiling of bioluminescence via photomultiplying cameras (*e.g.,* the Image Intensified Silicon Intensifier Target-ISIT; the Image Intensified Charge Coupled Device for Deep-sea Research, ICDeep; *e.g.,* Craig *et al.,* 2015). Alternatively, other imaging systems have been developed, that is, the extreme low-light working LuSEApher camera with photon counting capability (*e.g.,* Barbier *et al.,* 2012; Dominjon *et al.,* 2012)

Other means for measuring the bioluminescence of organisms are provided by deep-sea neutrino telescopes (Martini *et al.,* 2016; Aguzzi *et al.,* 2017). Their mooring-like towers cover the benthopelagic dimension and are primarily instrumented with thousands of photon-detecting sensors (*i.e.,* photomultiplier tubes, PMTs) (FIG. 2a–2c), capable of picturing the passage of neutrinos in the form of high-energy light. The main stimulation of organisms to emit light around those static structures comes on impact when swimming or as induced by turbulence behind them. The KM3NeT-Italia and ANTARES neutrino telescopes, off Capo Passero (Sicily, Western Ionian Sea) located at a depth of more than 2 km are an example of the three-dimensionality of those infrastructures (reviewed by Aguzzi *et al.,* 2019). Telescope moorings cover the benthopelagic dimension in the form of a cubic kilometer scale matrix of vertically extended, flexible strings which rise for hundreds of meters above the seabed (Sapienza and Riccobene, 2009).

2.5. Acoustic imaging

Deep-sea video monitoring of fauna is being integrated with novel acoustic (multibeam, high-frequency) cameras into efficient optoacoustic packages (Juanes, 2018) that, with an appropriate design, could be used in the search for putative life in exo-oceans (see TABLE 1). The Dual-frequency Identification Sonar (DIDSON) and Adaptive

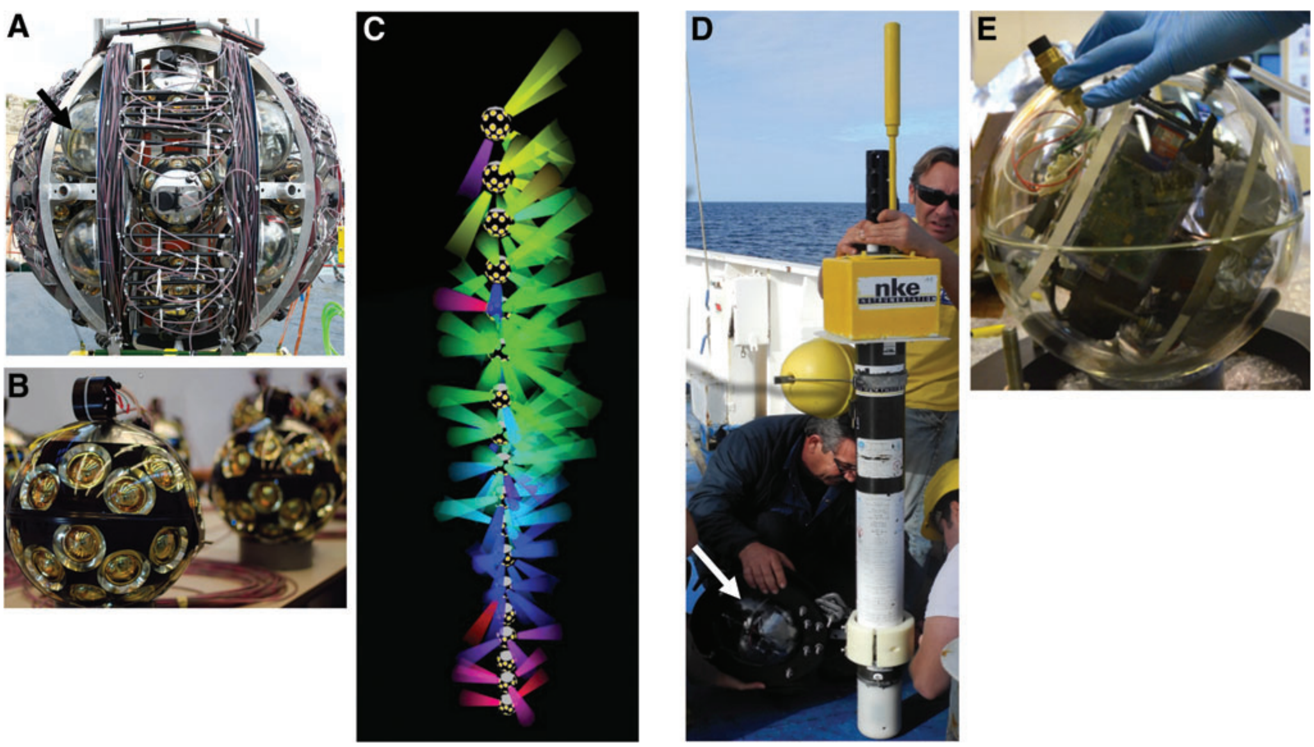

FIG. 2. Sensor devices hosted in depth-rated glass spheres. (**A**) Curled-up moored line of neutrino telescope spheres hosting PMTs, prior their deployment (the arrow indicates the element of the following plate, B). (**B**) Each single spherical unit where a set of PMTs is installed to face different angles. (**C**) Schematic representation of the extended moored line with all spherical units projected from the seabed, and whose PMTs are reading bioluminescence in all directions (color cones). (**D**) GUARD-One camera into a glass sphere connected to an Argo float (the arrow indicates the element of the following plate, E). (**E**) An enlargement of the glass sphere camera housing. Color images are available online.

Resolution Imaging Sonar (ARIS) can deliver three-dimensional images of organisms and map seabed features in aphotic environments, depending on organism size and ambient turbidity conditions (Aguzzi *et al.,* 2019). That type of assets does not require light to identify and scale objects within the field of view. Unfortunately, the active emission of sound is also another monitoring footprint to be considered in unknown ecological contexts.

2.6. Passive acoustic monitoring

Passive Acoustic Monitoring (PAM) by listening hydrophones provides relevant information on biological activity based on specific sound markers (*i.e.,* noise emission spectra) (see TABLE 1). In deep-sea areas on Earth, the types of organisms revealed by sound emissions cannot be identified with this sensor technology, unless we can associate their acoustic signaling with images (*e.g.,* Archer, 2018; Mouy *et al.,* 2018). This condition cannot be met for exo-oceans where no previous environmental knowledge exists, but the broad characterization of soundscapes and their geological and hydrographic processes are of high value, when crossed with the multiparametric data collection proposed with geochemical and oceanographic sensors. For example, the use of this technique on Earth revealed the presence of gas bubbling beyond the reach of optoacoustic imaging technologies and provided information on the extension of the phenomenon (Maksimov *et al.,* 2016).

2.7. Molecular-based technologies

The detection of potential life in exo-oceans could seek environmental DNA/RNA forms (eDNA/eRNA-like) within a structural framework as known from Earth (*e.g.,* the FISHbot initiative; Floyd, 2018) (see TABLE 1). Detection of nucleic acids may be measured via fluorescent dyes (indirect detection) or through nucleotide sequencing (direct detection). The former method relies on the binding of solubilized molecules with either double- or single-strand nucleic acids that interact with light at specific wavelengths. Fluorescence imaging devices (*i.e.,* microscopy or spectrometry) are capable of detecting a wide range of dye molecules with high sensitivity, each of which shows preferential binding substrate (Suseela *et al.,* 2018). However, false positives may occur when fluorescence dye imaging is applied to environmental samples. Inefficient staining, nonspecific binding to sample components, and autofluorescence of mineral particles under light excitation often interfere with efficient DNA/RNA detection (Li *et al.,* 2004).

Direct sequencing of eDNA/eRNA has become a cornerstone of future marine research (Scholin *et al.,* 2017), and the next generation of Environmental Sample Processor (ESP) on board mobile robotic platforms (see below) is contributing toward this goal (Zhang *et al.,* 2019). A promising technology for *in situ* nucleic acid identification, not yet suited for the marine medium, is offered by nanopore devices (Oxford Nanopore Technologies). These devices have been successfully tested in the International Space Station (Castro-Wallace *et al.,* 2017). Presently, the Search for Extra-Terrestrial Genomes (SETG) program is aiming to detect free nucleic acids based on nanopore sequencing technology (Carr *et al.,* 2017).

Direct and indirect methods of detection of nucleic acids may be used for identifying environmental nucleoside alternative structures such as xeno-nucleic acids (eXNA; Cleaves *et al.,* 2015). Single-Walled Carbon NanoTubes (SWCNTs) could also be used for the detection of eXNA (Gillen *et al.,* 2018).

Other life-tracing technologies could be based on *in situ* mass spectrometry, which is being developed to target a wide range of organic and inorganic compounds dissolved in marine water by mobile robotic platforms (see below) (*e.g.,* Wollschlager *et al.,* 2016). Additionally, the use of Lab-on-a-Chip (LOC) technologies should be advanced to facilitate miniaturized time-series measurements on those platforms (Beaton *et al.,* 2012). LOC could be used to trace metabolic products, based on the detection of free-circulating compounds through specifically designed markers, as suggested by Cassini-Huygens' recompiled information (Mathies *et al.,* 2017).

3. Marine Platforms and Their Networks for Exo-Ocean Exploration

The development of fixed and autonomous mobile platforms is revolutionizing our ability to explore the deep-sea benthic and pelagic environments, acquiring information at a high resolution not achievable with vessels (Wynn *et al.,* 2014; Aguzzi *et al.,* 2019). A wide spectrum of oceanographic, geochemical, optic, and acoustic sensors can be installed on those platforms to explore the seafloor, the subseafloor, and the water column variability, including the potential presence of extant life (see TABLE 1).

Different power sources are currently used on Earth-based systems to sustain the functioning of those platforms. A continuous provision of energy can be given to fixed infrastructures by fiber optic cables or, if that is not possible, using *in situ* marine renewable energy resources such as water column turbines and vertical tidal oscillators, and even solar panels (Favali *et al.,* 2015). In the case of exo-oceans, water turbines can be used if sufficiently strong and temporally sustained hydrodynamic forces exist. Space missions are currently using energy provision through radioactive decay (Stone *et al.,* 2016; Cwik *et al.,* 2019) by a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) as the core of Radioisotope Power Systems (RPS) (NASA, 2011), as in the case of the Mars Science Laboratory (Loren *et al.,* 2013; Holgate *et al.,* 2015). A nuclear battery efficiently converting heat into electricity and generating electrical power in smaller increments could be used for a variety of space missions, from the vacuum of the space to exo-oceanic contexts. Such a solution may last up to decades, and it may be used in future autonomous long-lasting marine and exo-oceanic exploration missions.

Acoustic or light-based modem technologies (Bai *et al.,* 2019; Han *et al.,* 2019; Shen *et al.,* 2019) are being developed for communication and hence inter-operability among mobile and fixed robotic platforms to increase their working autonomy (Del Rio *et al.,* 2011, 2018; Dunbabin and Marques, 2012; Wang *et al.,* 2017). Those intercommunication capabilities can be used for target tracking (Masmitja *et al.,* 2018, 2019), as navigational aids (McPhail and Pebody, 2009), or locating docking stations (Vallicrosa *et al.,* 2014).

In this framework, this section describes the status of technological developments of marine robotic platforms with different levels of autonomy and mobility that can be adapted and used for exo-ocean exploration, either in standalone modes or coupled together into cooperative networks (TABLE 2). It is important to note that network-based redundant and prolonged data collection is of relevance to highlight spatiotemporal variations in deep-sea ecological processes (Aguzzi *et al.,* 2019).

3.1. Cryobots

Enceladus exo-ocean exploration should be based on penetrating robots as melting probes. The NASA-funded cryobot named VALKYRIE, developed at Stone Aerospace (Texas, USA), consists of a laser beamed down to a fiber optic cable as a heat source to melt the ice, and it was successfully tested in an Alaskan glacier (Stone *et al.,* 2014, 2018). Insights on potential pitfalls and issues related to the penetration of ice shells could be gained from the results of similar trials carried out in Antarctic subglacial lakes (Siegert, 2018). In particular, Lake Vostok might be one of the best examples to be compared to the exploration of exo-oceans by being separated from the rest of Earth's atmosphere by a 4 km thick ice layer, which had to be drilled in order to access the liquid water (Siegert *et al.,* 2016). Unfortunately, in Lake Vostok the drill bit became damaged due to the thermal shock caused by contact with the lake water and produced an overspill of the drilling fluid (kerosene) that compromised the lake water analysis. The limits of the drilling technology used in Lake Vostok were overcome during the exploration of Lake Whillans, where a clean hot water drilling technology was used, making this lake the first successfully explored Antarctic subglacial lake (Michaud *et al.,* 2016). Many drilling technologies are currently under investigation and under development for the exploration of the Antarctic (Talalay, 2020) subglacial lakes and Solar System worlds (Badescu and Zacny, 2018).

In relation to exo-oceans, similar melting probes could be conceived as actively ''driving'' through the ice, while taking and analyzing samples (*e.g.,* Lucchetti *et al.,* 2017). Active exploration could be performed while penetrating the ice, in order to detect remnants of life that were frozen in the ice when the shell ruptured. In particular, the VALKYRIE cryobot had an early on-board meltwater sampling system and an autonomous algorithm to command sampling (Clark *et al.,* 2017).

3.2. Observatories

Multiparametric seafloor observatories, receiving power and transferring data via telecommunication cables, are currently deployed on Earth's seabed (Danovaro *et al.,* 2017). These structures allow for highly integrated multiparametric environmental and biological data collection in benthic realms that can be extended to the pelagic ones through depth profiling yo-yo probes (*i.e.,* performing cyclic water column ascent and descent; *e.g.,* Fujii and Jamieson, 2016; Fanelli *et al.,* 2019). Such platforms are open windows of the continental margin, from coastal areas to abyssal plains, to remotely study in real time life activity and its responses to environmental changes (Aguzzi *et al.,* 2019). For example, on Earth, compacted versions of these observatories have been successfully deployed in the deep sea close to hydrothermal vents, with cable-to-shore or in a stand-alone (*i.e.,* moored) fashion, enabling a remote and long-lasting monitoring of biological components and environmental variables at hydrothermal vent sites (*e.g.,* Colaço *et al.,* 2011; Cuvelier *et al.,* 2017). On Enceladus, these types of platforms may provide long-lasting Eulerian measurements of the exo-oceanic proximal water mass characteristics, alerting scientists in the case of detection of any relevant transient object.

Such fixed platforms are used to further control docked mobile platforms (see next section and TABLE 2). Their operational value for exo-ocean exploration resides in the necessity to deploy fixed nodes below the ice shell, capable of releasing mobile platforms, providing communications capability and power energy, permitting sampling and exploration of a larger area, while yo-yo probes move cyclically from the bottom of the ice shell through the underlying water column.

3.3. Crawlers and rovers

Autonomous or tethered crawlers are mobile multiparametric platforms, moving on the seabed on caterpillars (Flögel *et al.,* 2018). They are used to expand the biological and environmental monitoring area around cabled nodes (Aguzzi *et al.,* 2015; Thomsen *et al.,* 2017). Crawlers are known as Internet Operated Vehicles (IOVs) and have the advantage of great bandwidth with the onshore station, allowing real-time navigation capability and data collection/ transmission to land via interacting web interfaces (Purser *et al.,* 2013). Deep-sea applications of crawler technology can be found in the study of cold seeps (Chatzievangelou *et al.,* 2016; Doya *et al.,* 2017) and the envisaged monitoring of ecological impacts at mining (Chatzievangelou *et al.,* 2017). For Enceladus, crawler action may increase the monitoring radius around nodes providing larger monitoring coverage.

Presently, increasing autonomy in crawler missions and data collection is being implemented through technical solutions for full cable-independence via inductive powering (*i.e.,* recharging is based on new depth-rated lithium batteries; Brandt *et al.,* 2016) and autonomous navigation (Wehde *et al.,* 2019). Rover (*i.e.,* wheeled vehicle) technology is also being implemented as a nontethered alternative to crawlers, being operative through a vessel-deployable docking station (Flögel, 2015; Wedler *et al.,* 2015; Flögel *et al.,* 2018). For example, the benthic mobile physiology laboratory rover has been tested in the northeastern Pacific at 4000 m depth and 220 km west of the central California coast (McGill *et al.,* 2007).

Crawlers and rovers are of relevance for developing robotic operations practices during exo-ocean explorations, since both can move beneath the ice shells even in the presence of currents, waiting for commands from a distant control center. Reduced size/weight material and positively buoyant versions of those platforms could move upside-down below the ice shell. Crawlers could even release floats and sink to the seafloor for upside operations. With the increase of their autonomous driving capability and multiparametric monitoring capacity, crawlers may be transformed in the future into a marine analog of the Mars Science Laboratory (Loren *et al.,* 2013, Holgate *et al.,* 2015), but adaptable to Enceladus.

Platforms similar to the crawler, as the Buoyant Rover for Under-Ice Exploration (BRUIE; Berisford *et al.,* 2013),

TABLE 2. MULTIPARAMETRIC PLATFORMS WITH DIFFERENT OPERATIVE RANGES AND AUTONOMY, TO BE POTENTIALLY ADAPTED FOR EXO-OCEAN EXPLORATION

Operational environment	*Depth*	*Strategy of design*	*Model*	*Development stage*	*Monitoring strategy*	*Source*
Pelagic	Superficial/Coastal	Biomimetic	Robo-Tuna	Implementation	Potentially Lagrangian[a]	Anderson and Chhabra, 2002
	Superficial/Coastal	Biomimetic	Robo-Salmon	Implementation	Potentially Lagrangian[a]	McColgan and McGookin, 2014
	Superficial/Coastal	Biomimetic	Robo-Manta	Implementation	Potentially Lagrangian[a]	Ikeda *et al.*, 2014
	Superficial/Coastal	Biomimetic	Robo-Octopus	Implementation	Potentially Lagrangian[a]	Cianchetti *et al.*, 2015
	Superficial/Coastal	Biomimetic	Robo-Jelly	Implementation	Potentially Lagrangian[a]	Villanueva *et al.*, 2009
	Superficial/Coastal	Biomimetic	SCUBA-Drone	Implementation	Eulerian	Carey, 2016
	Phreatic/Caves	Mechanic	Deep Phreatic Thermal Explorer (DEPTHX)	Operational	Potentially Eulerian-Lagrangian	Stone *et al.*, 2005
	Under-ice	Mechanic	Environmentally Non-Disturbing Under-ice Robotic Antarctic Explorer (ENDURANCE)	Operational	Potentially Eulerian-Lagrangian	Stone *et al.*, 2014
	Under-ice	Mechanic	Buoyant Rover for Under-Ice Exploration (BRUIE)	Under implementation	Eulerian	Jet Propulsion Laboratory, 2015b
	All depths	Mechanic	Mesobot	Operational	Eulerian-Lagrangian	Yoerger *et al.*, 2016
	All depths	Mechanic	Argo	Operational	Lagrangian	Riser *et al.*, 2016
	All depths	Mechanic	Hybrid Underwater Robotic Vehicle	Implementation	Eulerian-Lagrangian	Zuo *et al.*, 2015
	All depths	Mechanic	Autonomous Underwater Vehicles (AUVs, including Gliders)	Operational	Eulerian-Lagrangian	White *et al.*, 2016
	All depths	Mechanic	Leng AUV (Europa Explorer)	Under implementation	Eulerian-Lagrangian	Funke and Horneck, 2018
	All depths	Mechanic	Icefin	Under implementation	Eulerian-Lagrangian	Spears *et al.*, 2016
	All depths	Mechanic	Yo-Yo platforms	Operational	Eulerian	Fujii and Jamieson, 2016
Benthic	Superficial/Coastal	Biomimetic	Crabster	Operational	Potentially Lagrangian[a]	Jung-Yup and Bong-Huan, 2012
	Superficial/Coastal	Biomimetic	Robo-Lobsters	Under implementation	Potentially Lagrangian[a]	Hood, 2004
	All depths	Mechanic	Crawlers	Operational	Eulerian and potentially Lagrangian[b]	Purser *et al.*, 2013
	All depths	Mechanic	Rovers	Operational	Eulerian and potentially Lagrangian[b]	Henthorn *et al.*, 2010

[a]Operationally short-ranged, due to power limitations.
[b]Operationally medium-ranged, since docked to cabled observatories, but under implementation for long-range autonomy, as sustained by new high-pressure rated lithium batteries.

have already been tested in field deployments (Jet Propulsion Laboratory, 2015a). These positively buoyant platforms have two wheels endowed with teeth, allowing them to adhere to the ice shell bottom surface with anchoring capability at greatly reduced energy costs. These platforms have odometry-navigation capabilities and four thrusters allowing yaw control as well as the viewing angle of the camera to be independent of the vehicle's motion. Control and data transfer can be either realized by a tether or with an acoustic modem. BRUIEs are an ideal option for the exploration and monitoring of areas around fixed observatories (see the next section).

3.4. Deep-sea Autonomous Underwater Vehicles (AUVs)

AUVs are of high relevance for exo-ocean exploration due to their large versatility and autonomy. A relatively wide spectrum of sensor payloads can be installed on those platforms. AUVs' geophysical seafloor acoustic sensors can be programmed to autonomously map the seafloor and image the first meters of the subseafloor (*e.g.,* MBES; Lo Iacono *et al.,* 2008; Lurton, 2010; Lecours *et al.* 2016). Such seafloor imaging can be coupled with other oceanographic and geochemical tools to explore and quantify water column variability (Morris *et al.* 2014; Lecours *et al.* 2016) (see TABLE 1).

Autonomous underwater vehicles are presently preprogrammed, unmanned, self-propelled vehicles that navigate for various distances possibly using dead-reckoning systems (Paull *et al.,* 2014). Navigation systems are based on seafloor-relative velocity measurements through Doppler Velocity Log (DVL) instruments and Inertial Measurement Units (IMU). However, dead-reckoning systems need periodic adjustments in order to maintain an acceptable accuracy due to inherent errors and their accumulation over the time (Masmitja *et al.,* 2018, 2019). Usually, AUVs emerge on the sea surface to fix GPS positions or use a combination of Ultra Short BaseLine (USBL) acoustic communication or arrays of Long BaseLine (LBL) acoustic beacons positioned on the seafloor. Operational constraints related to an ice shell covering an exo-ocean may limit traditional navigation methods and require other approaches such as range-only single-beacon navigation (Masmitja *et al.* 2019).

Autonomous underwater vehicles are being coupled with cryobots (see previous crawlers and rovers section) in projects such as Subglacial Polar Ice Navigation, Descent, and Lake Exploration (SPINDLE) or Sub-Ice Marine Planetary Analog Ecosystems (SIMPLE), both funded by NASA (Stone *et al.,* 2016). A 20 km range hover-capable hybrid AUV, named Autonomous Rovers/airborne-radar Transects of the Environment beneath the McMurdo Ice Shelf (ARTEMIS), developed at Stone Aerospace[2], is used to perform long-range surveying of the under-ice ocean. The hybrid AUV/ROV Nereid-Under Ice (NUI; Woods Hole Oceanographic Institution) has performed near-seafloor surveys under the ice pack in the Arctic Ocean (Jakuba *et al.,* 2018). Presently, AutoSub 3 performed the most successful under-ice-shelf exploration to date at the Pine Island Glacier (McPhail *et al.,* 2009; Jenkins *et al.,* 2010). While these large AUVs are not suited for exo-ocean exploration, they offer platforms on which to test new technologies and autonomous methods in an analogous environment on Earth.

Underwater vehicle autonomy is presently implemented through permanent docking at cabled observatories (Wirtz *et al.,* 2012; Hildebrandt *et al.,* 2017). Such docking capabilities, similar to stationary ROVs presently used by the deep-sea oil industry, will allow AUVs to perform depth-rated water column ascents or descents from beneath ice shell locations (*e.g.,* ARTEMIS docking; Kimball *et al.,* 2018). A similar concept of remote control is represented by the Europa Underwater Probe ''Icefin.'' This AUV platform can be considered as an autonomous and remotely controlled small multiparametric probe designed to operate below the ice shell through a tether, and could also be used in exo-ocean exploration (Spears *et al.,* 2016).

Other innovative AUV approaches are based on novel emerging robotic technologies inspired by nature (*i.e.,* biomimicking designs) and are of great relevance for space missions and for exo-ocean exploration. Fish-inspired solutions may be of some utility (Menon *et al.,* 2007) due to component miniaturization (low volume/weight), robustness, mission cooperative behavior (*e.g.,* self-repair), and long-lasting autonomy (low-energy consumption) (*e.g.,* see Bluman *et al.* [2017] and Funke and Horneck [2018] for a conceptually analogous approach to the small cooperative units conceived for Mars land/atmospheric exploration). A new class of swimming robots (see TABLE 2) are currently being assembled with miniaturized sensor components and tested in coastal or shallow water areas (Degnarian and McCauley, 2016). In the near future, swarms of modular units (swarm-bot, or s-bot), showing some level of self-regrouping/self-repair capability and redundancy in data collection (Hunt, 2019), may prompt fine-tuned spatial coverage in Earth's deep-sea areas, to be later tested for space missions.

3.5. Drifting platforms

The Argo concept design[3] could be implemented and adapted to explore exo-oceans. These multiparametric autonomous and freely drifting devices are being used to collect salinity and temperature in the water column down to 2000 m depth through consecutive cycles of ascent and descent (Riser *et al.,* 2016). When at surface, platforms transmit data via satellite before starting a new cycle. Presently, below ice-shelf observations have been successfully carried out with floats in a prolonged and autonomous fashion (Dutrieux *et al.,* 2018; Lee *et al.,* 2018), also in challenging contexts of unpredictable hydrodynamic regimes (Troesch *et al.,* 2018).

In the past 10 years, Argo platforms have been implemented with new sensors and miniaturized analyzers such as fluorescence for chlorophyll-*a* and dissolved organic material, or oxygen, pH, and pCO_2 (Riser *et al.,* 2016; Stanev *et al.,* 2017). Imaging devices are getting small enough to be integrated into an Argo structure (see FIG. 2) with hardware supports capable of running artificial intelligence–

[2]http://stoneaerospace.com/artemis

[3]http://www.argo.ucsd.edu

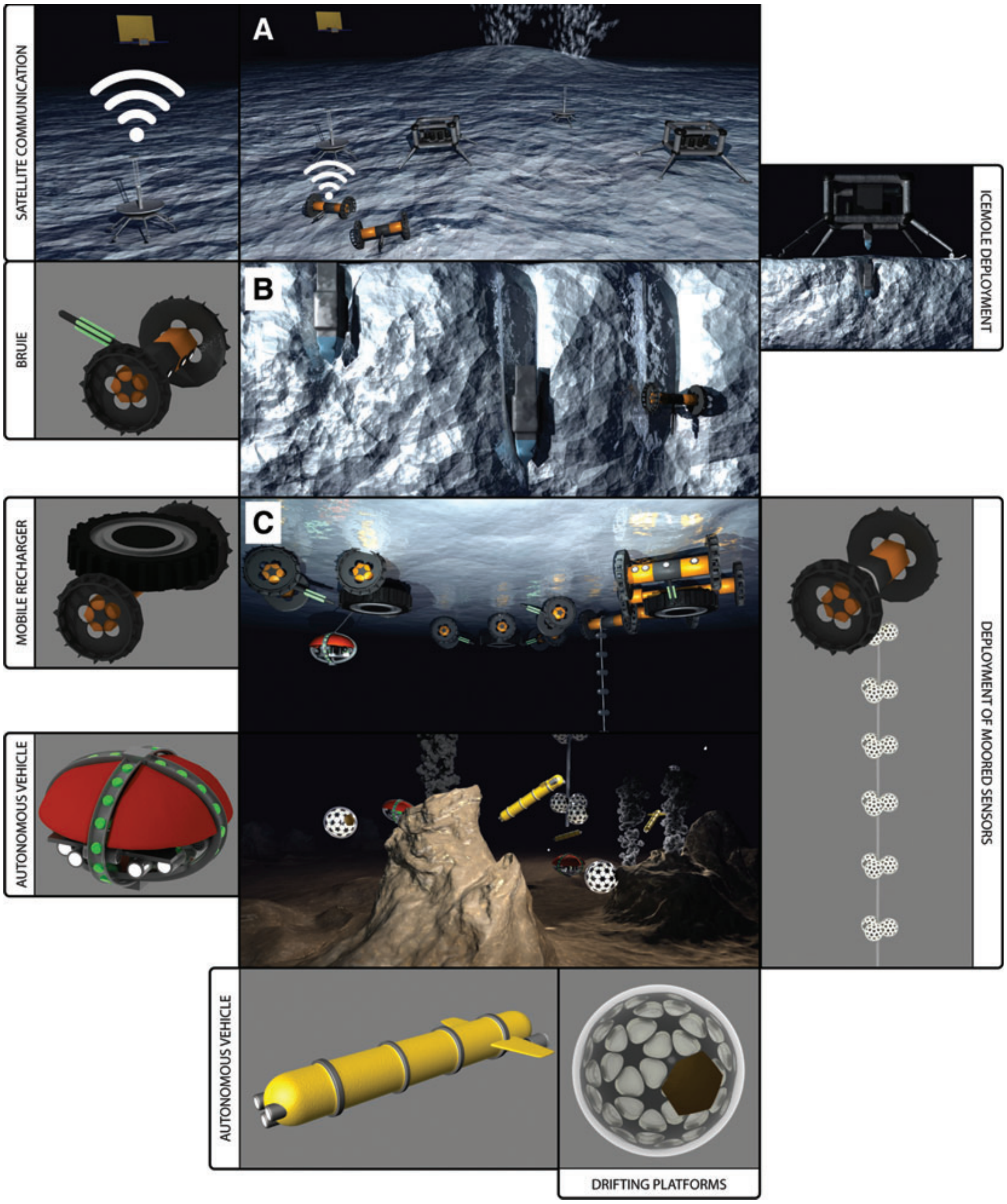

FIG. 3. The implementation of the mission concept design for Enceladus exo-ocean exploration by a network of fixed and mobile cooperative platforms. (**A**) Landing and platform delivery on surface. (**B**) Platform penetration. (**C**) Platform dispersion below ice, water mass reckoning, and the releasing of drifting assets. Color images are available online.

based computer vision for the detection of pelagic organisms (Marini *et al.,* 2018a, 2018b). Those devices are being used to study a still evanescent life component of our oceans, which is represented by large aggregates (deep-scattering layers) of bathymetrically displacing organisms, being hence of utility to scan large volumes of Enceladus' exo-ocean for similar purposes.

4. A Pathway for Exo-Ocean Exploration

A possible mission scenario can be globally drafted, according to previously presented sensor and platform technologies, following different steps described by previous authors (*e.g.,* Cwik *et al.,* 2019). Our concept, summarized in FIG. 3, consists of three phases: Phase 1 is landing and platform delivery on the surface (only synthetically portrayed); Phase 2 is platform penetration (already treated in the section on cryobots above); and Phase 3 is platform dispersion below ice and the release of drifting assets.

4.1. Landing, platform delivery on surface, and data communication capability

Enceladus exploration scenarios are based on the presence of a fixed lander system that should arrive at a safe distance from active geysers and then should release cryobots that penetrate the ice shell (Dachwald *et al.,* 2014; Konstantinidis *et al.,* 2015). While descending, each cryobot should unroll a thin cable fixed to the lander and capable of transferring power and data. That cable should resist the mechanical stress of ice closing after its passage; such a stretch and compression reliance can be achieved by a specific coating (*e.g.,* Kevlar).

The releasing platform should remain on the surface of the icy moon in order to transmit data back from the exo-ocean's moon to Earth. Such a platform should be responsible for all data communication and transmission, suffering different constraints which should be carefully taken into account because of the limited navigation autonomy of mobile platforms (as described in the following sections).

The latency associated with deep space communications (79 ± 8.3 min for Enceladus) and the communication dropout expected due to occlusion by orbital bodies (approximately 16.5 h for every 33 h on Enceladus) prevent real-time and continuous communication. The platform hosting the scientific instruments would autonomously prioritize objectives to maximize its efficiency while obeying resource and time constraints as well as completing mandatory activities, such as rendezvous for communication. To increase the effectiveness of the scientific operations, methods for semi-autonomous and autonomous data collection would be designed and implemented for identifying regions of scientific interest (Zhang *et al.,* 2012, 2016; Flexas *et al.,* 2018), scientifically relevant features like hydrothermal vents (Branch *et al.* 2018), and select targets on which to perform observations (Estlin *et al.,* 2012, Francis *et al.,* 2017). A strategy for high-level human guidance is required to allow for refinement of autonomous behaviors based on analysis of data by scientists on Earth.

The large amount of data collected *in situ* cannot be entirely transmitted to Earth. Due to strict data communication constraints, it is mandatory to equip the observation platforms with software solutions able to identify and transmit only the relevant information collected. This problem happens also in deep-sea research, where solutions are provided by data science, pattern analysis, and artificial intelligence methodologies (Skiena, 2017; Aguzzi *et al.,* 2019). Simple computer vision algorithms can be executed on board platforms' imaging asset, to identify any subject different from the water or seabed itself (Corgnati *et al.,* 2016; Marini *et al.,* 2018a). General approaches based on image enhancement, differencing, and background subtraction methods can be used to discard irrelevant information (Moeslund, 2012; Peters, 2017); for example, in the case of water column, ice shell, or seabed surfaces, changes in patterns would be slower with respect to traveling objects. This information can be transmitted to Earth through periodic reports and analyzed by expert scientists. Specific algorithms could then be trained to recognize and classify relevant subjects (*e.g.,* suspended particulate, living organisms). Then the updated algorithms could be sent back to the *in situ* platforms to improve their effectiveness.

4.2. Platform dispersion below ice and water mass reckoning

Once deployed in the exo-ocean, the cryobot should act as a fixed observatory equipped with a minimal set of scientific instruments for estimating the ocean's environmental conditions. According to a positive evaluation of those conditions, the cryobots should release the BRUIEs equipped with multiparametric sensors, which would start the exo-ocean observation of the surroundings of the fixed platform. These mobile units should be equipped with wireless intercommunication capability via acoustic or light-based modem technologies (see the previous section). Data download recharging and battery could be performed by inductive pinless connection (*e.g.,* Fonn model by Wi-Sub[4]; Wehde *et al.,* 2019) among BRUIEs and/or between the BRUIEs and the cryobot.

Those moving platforms could be endowed with high-sensitivity cameras and acoustic imaging equipment (see TABLE 1), allowing for detection of organisms under extreme low light with a reduced footprint (*i.e.,* potentially harmful light effects in aphotic environments). At the same time, photomultiplier tubes (PMTs) and passive acoustic technologies (PAM) should be included as well, to measure bioluminescence presence and characterize soundscapes in terms of biophony (as analogous to cetacean-like communication) and geophony (providing important data on background oceanographic and geological processes). Molecular sensors (*e.g.,* nanopore sequencing technology) and mass spectrometry devices could complete the detection capability of any putative life, allowing organism traceability well beyond previously described sensor assets.

Some of the BRUIEs could be endowed with moored lines replicating the above-described sensor asset, to be projected into the water mass in an initial reckoning phase at unknown hydrodynamic conditions (see FIG. 3). A Eulerian picturing of water masses could be carried out with sensors hosted in physically inert and depth/pressure-rated cases (*e.g.,* glass spheres equivalent to those used for neutrino telescope assets; FIG. 2d, 2e).

4.3. The release of drifting platforms

In a second stage, drifting platforms similar to Argo floats (*i.e.,* Bio-Argo; Claustre *et al.,* 2010) and even swarms of biomimicking robots capable of short-range swimming autonomy (see TABLE 2), could be released from moored projections of BRUIEs. A swarm of those walking or swimming platforms would allow local exploration of the water column or below the ice shell in areas where larger platforms could not arrive. These could deliver multidisciplinary redundant oceanographic, geochemical, and biological data within the shortest time span, to counteract any potential equipment failure under unknown oceanographic conditions (*e.g.,* Gissinger and Petitdemange, 2019).

Once the local hydrodynamics have been characterized, BRUIE platforms may release also another group of larger cooperatively communicating mobile robotic autonomous units as AUVs (see TABLE 2). These AUVs would be required to expand the monitoring radius around each node. These should permit autonomous but coordinated sampling activity, constituting a locally flexible cooperative network, similar to what has been conceived for marine surveying (*e.g.,* Thompson *et al.,* 2017) and defense (*e.g.,* Micro Unmanned Surface Vehicle Diving-USV from Aquabotix Technology Corporation).

[4]http://www.wisub.com/products/fonn

4.4. A strategy for exo-ocean platform testing

The implementation and testing of exo-ocean life-detection technologies could be performed in relevant deep-sea environments on Earth, currently endowed with flexible monitoring benthopelagic networks of cabled fixed and mobile platforms. All these processes should involve marine scientists and aerospace engineers, who should be consulted for different mission stages of conceptualization, planning, and development. Having space agencies test their technologies at deep-sea monitoring networks will allow us to tie together the necessities for exploring remote ecosystems on Earth in order to explore extraterrestrial ones.

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Abbreviations Used

AUVs = autonomous underwater vehicles
BRUIE = Buoyant Rover for Under-Ice Exploration
CTD = Conductivity-Temperature-Density
eDNA = environmental DNA
eRNA = environmental RNA
eXNA = xeno-nucleic acids
LOC = Lab-on-a-Chip
MBES = Multibeam Echo Sounders
PAM = passive acoustic monitoring
PMTs = photomultiplier tubes